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MEASUREMENT OF RAPIDLY VARYING HYDRAULIC FLOW RATES BY ULTRASONIC WAVES

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MEASUREMENT OF RAPIDLY VARYING HYDRAULIC FLOW RATES BY ULTRASONIC WAVES[1]

P. Alais[2], J. C. Demarais[3]

ABSTRACT. The study of unsteady phenomena in hydraulics implies the measurement of instantaneous flow rates of the liquids circulating in the pipes. It is desirable to add a minimum of perturbation in the circuits. This eliminates in practice all pressure drop devices or mobile mechanical parts. The method presented in this paper makes use of the convection phenomenon of an ultrasonic wave by the flow. After recalling the main methods in common use, the mechanical and electronic solutions retained are presented, as well as the results obtained with instruments of various capacities designed at O.N.E.R.A.

I. Introduction /62*

The measurement of liquid flow rates has been performed satisfactorily for some time. The more advanced solutions use a mechanical part exposed to the velocity of the fluid with the resultant phenomenon being analyzed by associated mechanical or electronic devices. The measurements are frequently industrial in character allowing some degree of integration since the qualities of high-speed response generally only have a secondary interest. Nevertheless, some devices, used under suitable conditions, are capable of detecting variations in velocity in a hundredth of a second.

The presence of an obstacle placed in the flow can be troublesome, even prohibitive, more particularly when it is necessary to analyze circuits which are supposed to preserve all their geometrical characteristics. It is not possible, in this case, to add on a supplementary device modifying the duct cross-sections which would have as its consequence a change in the dynamic

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1. Study made within the scope of a CNES contract.

2. Professor at the University of Paris. Part-time O.N.E.R.A. consultant.

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* Numbers in the margin indicate pagination in the foreign text.

characteristics of the system. The methods based on the detection of electrical potentials created within the fluid or on the modification of the wave propagation time in this medium in motion are, in principle, much more favorable. Since they do not introduce new components into the pipes, they are capable of following high-speed variations of velocity and it becomes possible to make a fine-grain analysis of the circuit studied and to understand its actual behavior.

This condition is especially desirable in the study of mechanical and hydraulic parameters capable of contributing, by pairing with the combustion chamber or the structure, to the appearance and maintenance of instabilities in liquid-fueled rockets, a phenomenon known by the term "POGO effect." An analysis of this abnormal operation proved to be necessary within the development cycle of the Diamant launch vehicle. O.N.E.R.A. was then tasked by CNES, in collaboration with SEP (European Propulsion Company - Société Européenne de Propulsion), with basic and experimental research on this subject. In order to successfully accomplish the simulation research, both on the test installations for investigations on non-uniform hydraulics as well as with actual cases of combustion, the design of flow meters with a near real-time response turned out to be absolutely necessary. Since O.N.E.R.A. was familiar with the works presently being done on ultrasonic measurement of flows at the Laboratory of Physical Mechanics at Saint-Cyr, the principle was adopted and an apparatus was developed which was more particularly suited for the high-speed measurement of the flow of liquid fuels under pressure. The mechanical and electronic solutions used are reported in this article after a review of the chief methods generally used.

II. Principles of Various Methods For Measuring Liquid Flow Rates

II.1. Perturbative Methods

(1) The flow meters using the Venturi effect relate the measurement of the flow rate to that of a differential pressure and are quite attractive in that they include no movable components. Unfortunately, in order to gain sufficient precision in most cases, it is necessary to apply a large correction as a function of the system of flow and nature of the fluid. On the other hand, the perturbation necessarily applied to the flow in order to create the Venturi difference in pressure makes this method quite unreliable for flow rates with high-speed fluctuations.

(2) The most widespread measurements of flow rate made at the present time still make use of mechanical parts driven in rotation by the flow. The theory of these measuring devices is still more often than not couched in rather crude terms and only an empirical development has allowed producing an acceptable precision by such methods. This is especially noteworthy, on occasion, since some flow meters of this type are reputed to supply the value of the mass flow with a relative error on the order of 10^{-3} within a relatively wide range of flow systems. The chief disadvantage of these apparatus in their industrial use is their short service life which essentially occurs owing to the wear and fouling of the moving parts. In addition, the inertia of the rotor only allows ascertaining the mean flow arising out of a time function of the size of the device whereas some miniature rotors developed at O.N.E.R.A. have allowed reaching response times on the order of 10^{-2}s [1]. Furthermore, the measurement of the angular velocity of the current meter is acquired by the frequency of passage of the blades in front of a sensor and it becomes impossible to have a datum out of the speedy fluctuations of a low flow rate whose characteristic time can become less than the time separating the movement of two neighboring blades.

II.2. Non-Perturbative Methods

During the last few years new methods have been offered the users and, although the former do not dominate the market owing to their relative imperfections springing from their recent development, they do, nevertheless, provide more attractive prospects. These are the so-called non-perturbative methods, in this meaning that the measurement is carried out without either modifying the flow or the pipe cross-section, sometimes without inserting a special pipe.

(1) The first apparatus of this type were the electromagnetic flow meters using the measurement of the electrical field induced by the flow of the liquid into a magnetic field created by the apparatus.

This method cannot, strictly speaking, be applied other than to conductive liquids. However, it is enough, in practice, to have a rather low residual conductivity (for example, the latter for ordinary water is usually rather high) for measurement of the induced potential to be possible. The method has available a rather great flexibility in the selection of the geometry of the magnetic field and electrodes share in the measurement of the induced voltage. It thereby requires all the engineer's art to profit from this so as to produce as representative as possible a potential of the flow rate. This method supplies the instantaneous flow rate whereas the measurement of a low potential with a very weak current requires a certain time constant. The apparatus of this type are produced industrially and typically supply a precision of ± 1% [2, 3].

(2) The measurement of the local velocity of a flow can be carried out by the measurement of the Doppler effect produced on a beam by reflecting particles transported by the flow. This method is presently being developed at O.N.E.R.A. for investigation of a high-temperature gas jet using a laser beam reflected by dusts injected into the jet. It was likewise developed by American oceanographers in order to measure ocean currents. The effect used here was the diffraction of an ultrasonic wave by plankton particles [4]. More recently, the proposal was made in France for an apparatus to mesure the blood flow rate also making use of the Doppler effect on an ultrasonic beam diffracted by blood corpuscles. These methods only allow definition of the flow rate usually with a moderate precision and are only really justified by very special measuring conditions whereby all other methods are impossible.

(3) A third method, the one we shall take up below, consists in utilizing the phenomenon of convection of an ultrasonic wave by the flow. However, /63 instead of calling upon the Doppler effect which is a consequence of it, the proposal is made to measure the propagation anisotropy caused by motion of the fluid. The modification contributed by this latter motion to ultrasonic propagation is only simple when the ultrasonic wavelength remains small with respect to the length of non-uniformity which is characteristic of the flow, a condition practically corresponding to that of the geometrical optics (or geometrical acoustics) in an environment with variable sign (or variable sonic speed). When this condition is fulfilled, it is possible to make a local study of the phenomenon as if the flow was uniform and the linearized equations of the acoustics confirm that the group velocity of the ultrasonic beam results from the vectorial summation of the flow and of the group velocity in absence of flow. This result was clear on a preliminary basis since it is the fluid itself which "carries the wave." The most simple application of the ultrasonic convection effect is the measurement of an ocean or river current.

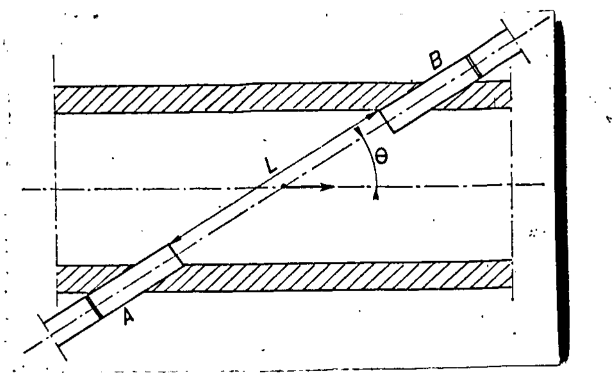

Figure 1. Principle of velocity measurement by the ultrasonic method.

Figure 1 shows a line of ultrasonic transmission made up of transducers A and B capable of transmitting or receiving a semi-flat beam according to direction AB. When this line is immersed in a uniform current with velocity V inclined by angle θ with AB, the velocities of phases according to direction AB will be respectively C + V cos θ, from A to B, and C - V cos θ, from B to A. The difference in travel time of the wave according to whether it is propagated in one direction or another is

$$\Delta t = \frac{l}{c - V\cos\theta} - \frac{l}{c + V\cos\theta} = \frac{2\,lV\cos\theta}{c^2 - V^2\cos^2\theta} \simeq \frac{2l}{c^2} V\cos\theta,$$

approximately to the second order with V/C, a parameter which remains, in practice, quite small and, in general, less than 10^{-2}. This difference Δt is proportional to the component of flow according to the ultrasonic beam.

When the irregularities of flow appear on path AB over distances which are, nevertheless, great with respect to the wavelength of the beam transmitted by A or B, it is always possible to fraction the path AB into lengths ≪ dl ≫ with which the propagation anisotropy produces the basic delay

$$dt = \frac{V\cos\theta}{c^2}\, dl,$$

such that the total delay taken on by the wave going from B to A with the wave going from A to B,

$$\Delta t = 2\int_{AB} \frac{V\cos\theta}{c^2}\, dl = \frac{2}{c^2}\int_{AB} \vec{V}.\vec{dl},$$

is found to be connected to the circulation of the velocity vector according to the rectilinear path AB. In the case where the transducers A and B are arranged on the walls of a cylindrical pipe traveled through by a stationary flow likewise cylindrical, it may basically be ascertained that the delay Δt is connected to the integral $\ll I \gg$ of the velocity profile with the chord $\alpha\beta$, projection of AB on the normal flow cross section:

$$\Delta t = \frac{2I}{c^2}, \quad I = \int_{\alpha\beta} V dl.$$

The quantity which can be measured, i.e. the delay Δt, is not connected with the flow rate which is an integral of the velocity profile on the cross section, but to the integral of this profile on one chord. For a known system, a laminar one for example, a simple constant correction can be applied. However, when the range of systems is great, this correction can vary appreciably. Nevertheless, in many practical cases, a turbulent flow system is gained as soon as the flow velocity exceeds several cm/s, and the profile of velocities no longer varies appreciably which allows recovery of the flow rate by a known correction factor with a precision on the order of 1% [4, 5, 6].

III. General Characteristics of Ultrasonic Methods Used In Flow Rate Measurement

In the problems of flow rate measurement presented by the study of the POGO effect, it is necessary to obtain the instantaneous flow rate with a time constant on the order of a millisecond since the flow rate can be affected by fluctuations whose spectrum can be spread out as much as 100 Hz. It is, furthermore, absolutely necessary to not modify the geometry of flow under penalty of completely deforming the oscillatory phenomena studied. Only non-perturbative methods can be used and, among these, the last ultrasonic method fulfills the absolutely necessary conditions of high-speed measurement and precision. Indeed, the speed of measurement is related to the propagation time of the ultrasonic wave from one transducer to the other. Thus, in the case of a pipe with a 200 mm diameter and an obliqueness suitable for the ultrasonic path, this time is on the order of 200 microseconds for water. It also forms a lower limit of the measurement time. In the example mentioned, it would not be possible to reach by such a method fluctuations of flow rate with a frequency greater than 5 kHz. Since this limitation is granted, as well as the fact that the measurement supplies the integral of the velocity profile on a chord and not on the cross section, the advantage of this method is that it amounts to a time measurement which is easy to record and establish causes of error. Finally, it is possible to classify these latter causes of error into four categories:

(a) The error, hydrodynamic in nature, in the corrective factor to be applied to express the flow rate beginning from the integral of the velocity profile on a chord. Entering into this error are the local perturbations caused by the bulging or hollowing out, contrived at the level of the wall to house the transducers. It is clear that this error can only be corrected by a measurement of mean flow rate by a precise calibration, since the extrapolation has to be made with measurements of fluctuations.

(b) The error, acoustic in nature, associated with interference phenomena capable of modifying the expression of delay Δt:

- difference in length of acoustic path when two pairs of transducers are used;

- difference in sonic velocity at the level of the two paths, either spatial in nature when the two transducer pairs are separated, or temporal in nature when the measurements of times of travel are not simultaneous. These differences in sonic velocity can be essentially related to high-speed spatial or temporal fluctuations of the temperature of the fluid or to fluctuations in the nature of the fluid; /64

- futhermore, sonic speed becomes a factor in the expression of delay Δt, and indeed the integral I is related to $C^2\Delta t$ requiring, in the case where slow and substantial variations appear in the nature or temperature of the fluid, the carrying out of continuous measurement of the sonic velocity and carrying out on an electronic basis, the correction of the multiplication by C^2.

(c) The "electromagnetic" error contributed by the transducers which are generally ceramic items installed so as to have the widest possible band pass. The damping desirable cannot be accomplished on a practical basis and these transducers have characteristics which are limited with regard to frequency and overvoltage causing a delay and distortion to be applied to the electro-acoustical conversion. The latter can have disastrous effects on the precision of the measurement owing to the fact that this delay as well as this distortion vary under the effect of external parameters such as temperature and local pressure imposed by the flow.

(d) The "electronic" error contributed by the receiving circuits and the measurement itself. In all cases, it concerns the measurement of a very short time since it is in the ratio V/C, of the rate of flow to the sonic velocity, with the sonic propagation time with distance AB or, by using the preceding example, on the order of 200 nanoseconds for a flow with a mean velocity of 1 meter per second.

The first technologies actually developed were inspired by the conventional method of measuring velocity of sound called the "Sing Around" in which the ultrasonic pulse received by the receiver from a delay line triggers the following pulse at the level of the transmitter. The frequency of relaxation of the periodic phenomenon produced is proportional to the sonic velocity of the environment propagating the pulse with a slight electronic error. If two such relaxers are used in which the apparent sonic velocity is modified by the flow in a symmetrical manner on both sides of the value observed at rest, as stated above, the measurement of the difference in frequency of the two relaxers supplies a signal related to

$$\Delta f = \frac{1}{t} - \frac{1}{t + \Delta t} \simeq \frac{\Delta t}{t^2} = \frac{2I}{l^2} \quad \left(t = \frac{l}{c}\right),$$

and consequently a crossing over has been made from the value of the sonic velocity to the difference of the expression of Δt.

One simple design [5] consists in calling upon two distinct relaxers. However, the errors related to the differences in path as well as the spatial fluctuations presented by the flow from one ultrasonic path to the other cause errors which can be great. Another method consists in using sequentially the same relaxer first in one direction and then in the other, making the difference in frequencies by means of an electronic memory. This method is, nevertheless, still sensitive to temporal fluctuations which are swifter than the sequence and, in addition, is not at all capable of high-speed flow rate measurement. One way of coping with these disadvantages is to cause the delay line to operate simultaneously in both directions thus allowing production of the double relaxation simultaneously with the same ultrasonic path and the same, or almost the same, time [6]. However this may be, it is clear that such a method can only lead to the measurement of flow rates varying slowly and does not allow coping with high-speed fluctuations. Only the "step by step" measurement of the time deviation Δt observed allows arriving at the shortest possible time constant. This measurement can be made beginning from ultrasonic pulses on condition that extreme precautions are taken owing to the fact that the rise time of the receiving signal cannot be lowered as much as desired and that there is a poor propagation of the high ultrasonic frequencies. The use of an amplitude discriminator in order to produce an accurate receiving time leads to an error related to the variations of receiving level caused by possible variations of the transmission or attenuation undergone by the wave in the propagation [7]. It is possible to be freed from the distortion or delay contributed by the electronic circuits by sequentially switching the latter [7]. However, in addition to the fact that it increases the time constant, this improvement cannot remove the electromechanical distortion caused at the level of the probes themselves. Instead of measuring the time deviation Δt beginning from isolated pulses, it can be advantageous to measure the phase deviation which it causes with sinusoidal signals. The advantages of this method will be discusssed below in section IV. The various designs of this type previously produced, nevertheless, call upon divisions of frequency which help measurement of the phase shift [8, 9] but do not allow protection of the small time constant which can be hoped for from the ultrasonic measurement.

IV. Characteristics of the Method Used

Some of the causes of error affecting ultrasonic technology will be discussed here. It will be noted that the "hydrodynamic" error, like the correction of multiplication by c^2, contributes to an error in the sensitivity of the apparatus. All the other errors are essentially at the origin of a zero error and it can be said that the measurement or the precise detection of zero flow represents the greatest difficulty to overcome in this method. It is the drift of zero which has turned out to be the largest error in practically all existing installations.

(1) One single pair of transducers should be used on a preferential basis. Transducers A and B will simultaneoulsy transmit the same signal in synchronism with each other and receive it with such delay as can be measured. This method has the advantage of simultaneously minimizing the "acoustic" error as well as the "electromechanical" error. The advantage of the first is obvious but, in the case of the "electromehcanical error" the advantage lies in the hope that the delay and distortion given to the signal by each tranducer are appreciably the same at transmission and at reception. In the process used, there can therefore be a compensation for the interfering effects connected with variations of temperature and pressure.

(2) The best way to minimize the error arising from the distortion, contributed as much by the transducers as by the electronic circuits, while at the same time preserving the response time, is to use oscillation trains transmitted synchronously by the probes at the highest possible frequency and with the longest possible duration, i.e. a little less than the time of ultrasonic travel. In reality, the phase shift caused is proportional to the carrier frequency:

$$\Delta\varphi = 2\pi f \Delta t = \frac{4\pi f}{c^2} I$$

and, since the errors owing to distortion of the signal bring on interfering phase rotations which are almost independent of the frequency used, any increase in the latter is the same as minimizing the absolute error committed with I, i.e. with the flow rate. Correlatively, in order to preserve the relative precision, it is necessary to be able to measure phase shifts corresponding to a hundred or even a thousand times the error $\delta\varphi$ admitted owing to the tranducers and circuits, i.e. phase shifts considerably greater than $\pi/2$ which suggests, in order to remove the ambiguity, carrying out a division of frequency by n with the receiving signals (cf. Figure 5), in this way authorizing measurement in the range $\pm$ n $\pi/2$. Naturally, the selection of frequency f and the division factor result from the following compromise: /65

The frequency f is essentially limited by the attenuation given to very high frequencies by the liquid environment and by the diffraction caused by the particles or gas bubbles which can be produced. This is why a frequency from 5 to 10 MHz can be considered as reasonable in many practical cases.

It will be seen that a phase measurement carried out with an error $\delta\varphi$ of $1°$ with a carrier frequency of 5 MHz is the same thing as carrying out the measurement of deviation Δt with an error less than a nanosecond.

The division factor n should be quite large, as has been stated above, in order for the range of measurement to be wide and the relative error to remain small. However, division factor n should remain small enough in order for the number p of gates produced beginning from several hundred initial oscillations to remain sufficiently great at the end of the frequency division. Indeed, the measurement of the final phase with the p gates produced in this way is the same thing as carrying out p times the measurement of Δt and keeping its mean value. This operation is only advantageous when p is quite high.

This method has been successfully used in the preparation of an oceanographic current meter at the Laboratory of Physical Mechanics and represents the new generation of an older prototype already successfully used [10]. Naturally, for oceanographic measurements, the smallest time constant desirable should not be less than 10 milliseconds and a frequency of transmission recurrence on the order of several hundred hertz is enough. In the problem discussed in this article, it is a matter, on the contrary, of lowering this time constant as much as possible. This assumes the use of a period of recurrence limited to the time required by the transmission, propagation and reception which, in the example used of a path requiring 200 μs for the propagation and a wave train of 100 μs, requires a period of a little more than 300 μs, i.e. a frequency of recurrence of 3 KHz.

Strictly speaking, the results obtained in this way make up a sampling of the phenomenon taken at a frequency limited by the minimum period of recurrence, and carried out through a spatio-temporal mean on the ultrasonic path. Leaving aside the limitations owing to the discrete character of the measurement, it is possible to seek to evaluate the inaccuracy owing to the averaging operation. Although it is difficult to calculate for any velocity profile whatever, it is, on the other hand, easy to specify its effects on a measurement of a flow with uniform profile varying rapidly. Since the measurement is linear, it is possible to make a Fourier analysis of the phenomenon and, since the mean is reduced in this special case to a time mean with the time of travel, each component of the Fourier spectrum corresponding to the pulse

ω is found to be reflected in the measurement by its mean:

$$\overline{e^{j\omega t}} = \frac{1}{\Delta t}\left[\frac{e^{j\omega t}}{j\omega}\right]_t^{t+\Delta t} = g e^{j\omega t},$$

at the same time granting:

$$g = \frac{e^{j\omega\Delta t} - 1}{j\omega\Delta t},$$

transfer coefficient of which Figure 2 shows the gradual development of the amplitude and the argument as a function of the reduced frequency $V = \frac{f}{f_0}$ defined by

$$\omega\Delta t = 2\pi V.$$

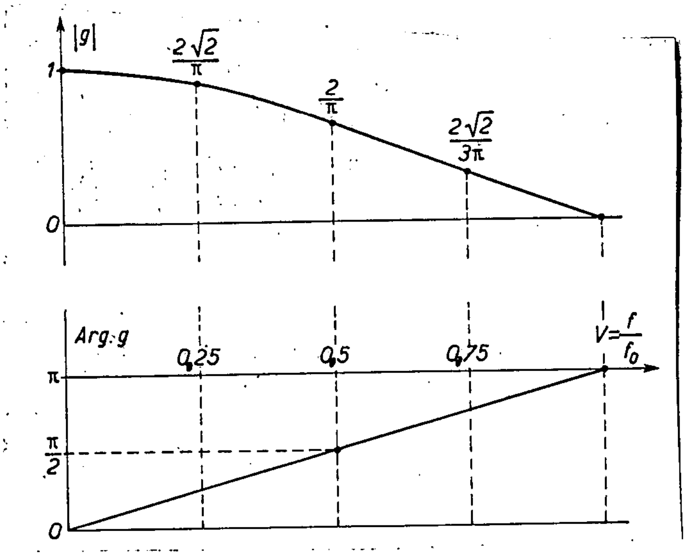

Figure 2. Transfer functions.

Note that in the example used where Δt = 200 μs and f_0 = 5000 Hz, the measurement of an oscillation of flow rate at 2500 Hz is considerably affected in amplitude and, above all, phase, since the signal is squared.

V. Experimental Designs

V.1. Principle of Electronic Installation Used (Figure 3)

The ultrasonic transducers used are made of ceramic and have a resonant frequency close to 5 MHz. The common transmission signal is supplied by a multivibrator covering a frequency range included between 4 and 6 MHz driven by a pulse generator supplying control gates 50 μs wide at a maximum frequency of recurrence of 5000 Hz. With each recurrence cycle, the pulse train produced is imposed simultaneously on the two ceramic transducers through adapting impedance amplifiers. The acoustic vibrations received at the level of each probe produce electrical signals transmitted to identical high-frequency amplifiers raising them to a level suitable for the triggering of shaping stages. The frequencies of the two pulse trains resulting from this last operation are divided by a number $n = 2^p$ (by passing into 4-bit binary counters with integrated circuits). The latter is a function of the range of flow rate desired, taking into account the diameter of the pipe and the inclination of the probes with respect to the flow axis (Figure 4), and the gates produced in this way have n/2 pulses. In addition, the binary counters used allow introduction of a time lag between these new gates by slowing down one of the n/4 pulse counters with respect to /66
the other. This operation causes the appearance, in the absence of flow, of a phase shift $\frac{\pi}{2}$ between the squared signal trains made up in this way. Using double-entry gates it is then easy to produce, beginning with these two trains, two groups of rectangular signals whose width varies inversely when the original phase shift $\frac{\pi}{2}$ is modified by the flow (Figure 5).

The latter are then sent on to conventional integrators produced with operational integrated amplifiers. A differential amplifier followed by a low-pass filter allows obtaining an analog voltage proportional to the velocity of the liquid in the pipe with this voltage able to energize a conventional recorder (Figure 6). The power supply of the system if provided from modular components placed in a standardized unit. The electronic part in its true sense is carried in a housing containing three plug-in printed circuit cards each of which performs a well specified function.

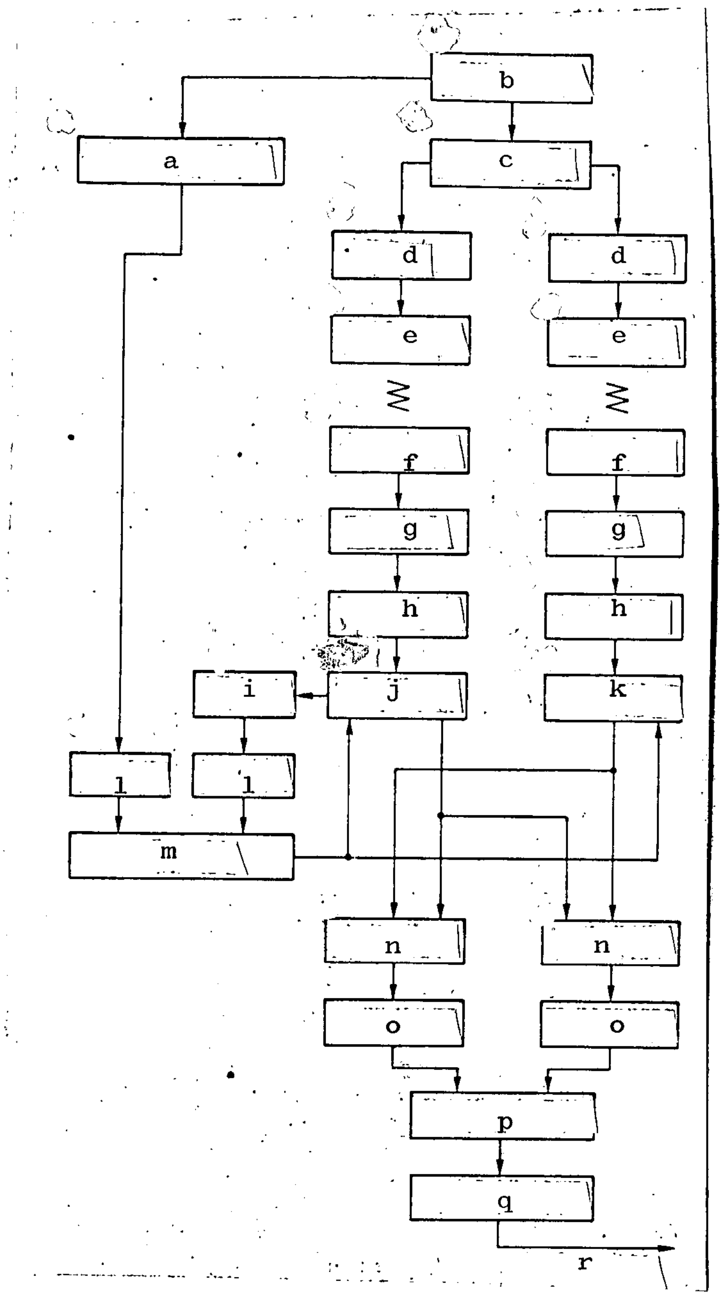

Figure 3. Electrical circuit.

Key:

a - receiving gate; b - transmitting time control; c - driven multivibrator; d - amplifier; e - transmitting probe; f - receiving probe; g - amplifier; h - shaping; i - divider; j - counting with phase shift; k - counting; l - shunt; m - reset-to-zero gate; n - phase-shift gate; o - integrator; p - differential amplifier; q - low-pass filter; r - recording.

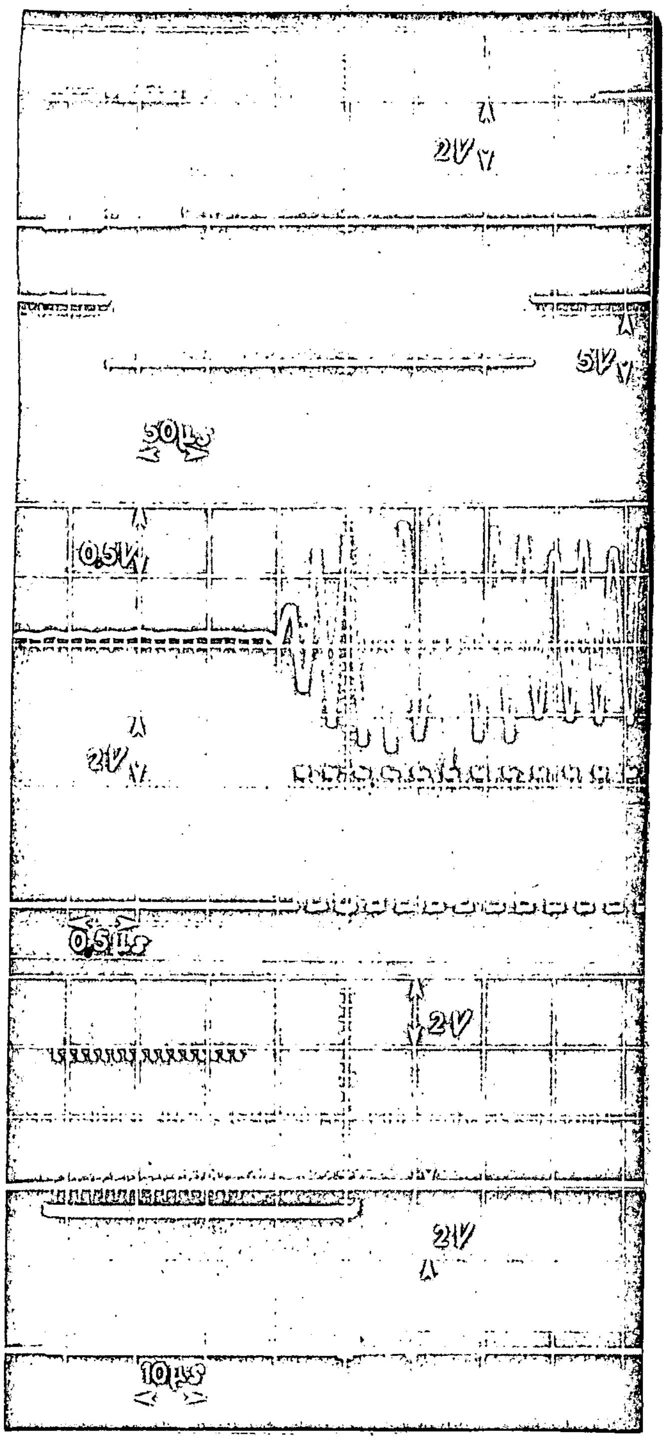

Figure 4. Recordings obtained.

V.2. Ultrasonic Probes Used

The probes developed are equipped with ceramic transducers made of zirconate and lead titanate. The small quality factor of these ceramic transducers allows them to operate in a wide frequency range and the high dielectric constant /67 permits the obtaining of low-impedance components. The stability of the various characteristics is given as excellent up to 200°C.

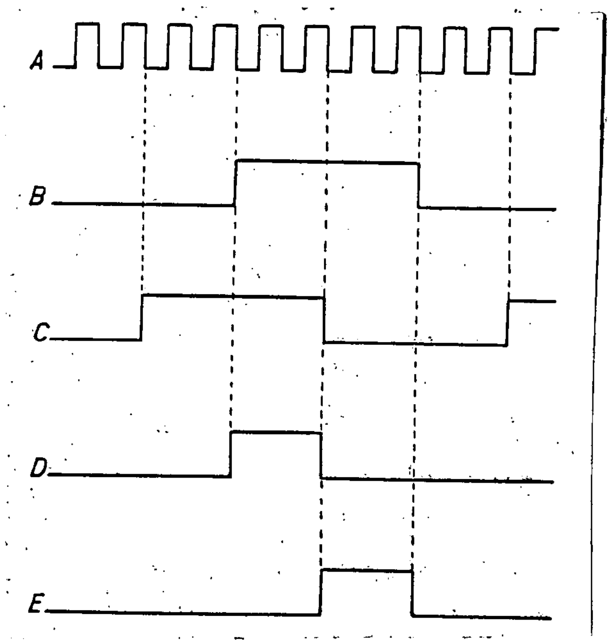

Figure 5. Processing of the signals.

A - Receiving signal, channels 1 and 2
B - Divided signal, channel 1
C - Divided signal, channel 2
D - Signal for integration 1
E - Signal for integration 2

These probes, designed to operate in the presence of corrosive liquids such as the oxidizing agents of combustion chambers for liquid propellants, can bear pressures going as high as several hundred bars. They appear in two parts (Figure 7).

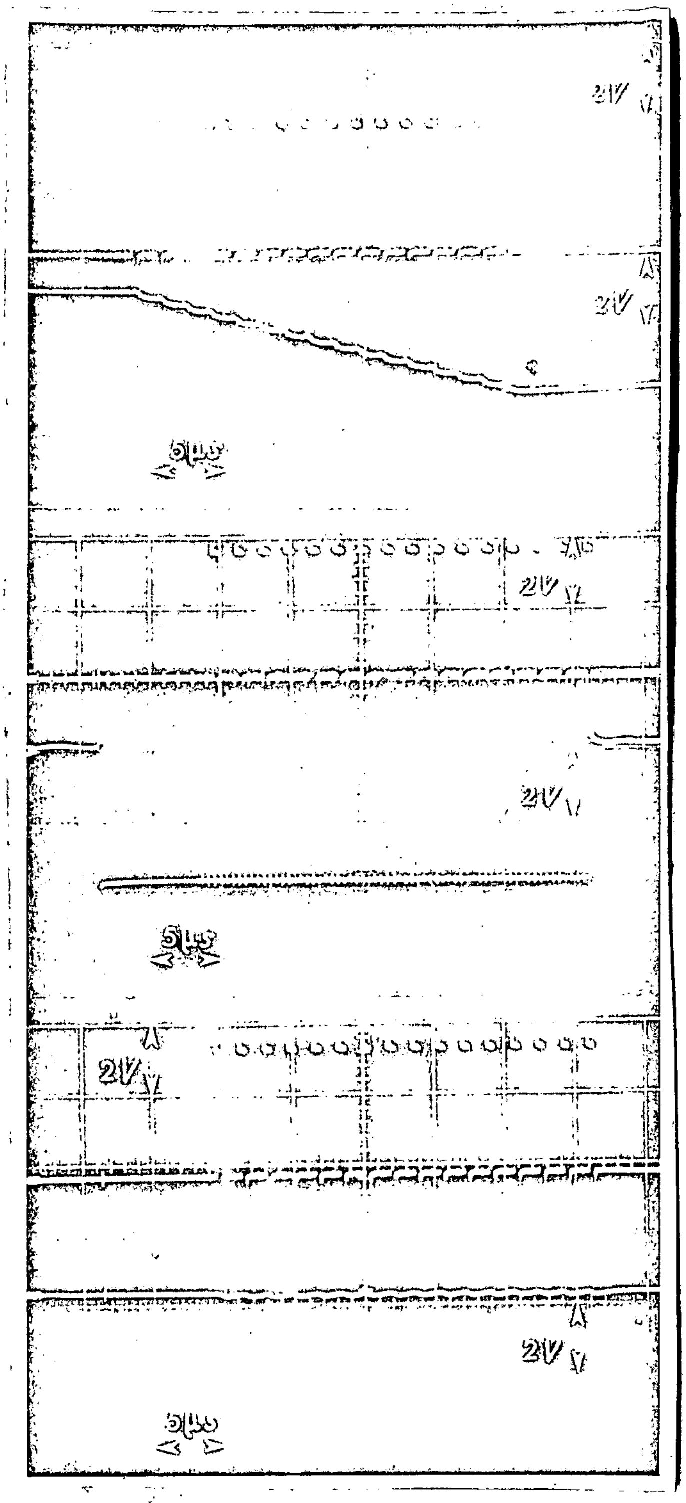

Figure 6. Signals after processing.

One part makes up the body of the probe in its true sense and encloses the ceramic transducer. The other part is made up by the connecting coaxial cable. These components are screwed into each other with the electrical connection of the inside surface of the ceramic transducer being made through the intermediary of a sliding contact made of brass. The outside surface of the transducer is connected electrically through the metal mass (stainless steel). The ceramic transducer is first of all attached to a lead component used as a "damper," itself connected directly with a contact made of brass, the system being held mechanically in an insulating cylinder. All of these attachments are made with an epoxy resin which is a conductor of electricity owing to its load of powdered silver. Around the ceramic transducer, slightly passing beyond the insulating cylinder, a strip of araldite is poured in order to avoid setting up any electrical contact between the two faces of the ceramic transducer during setup of the system in the probe body. The latter appears in the shape of a cap mode of stainless steel with a diameter of 6 mm, a length of 12 mm and a bottom 1 mm thick. The ceramic installation, a unit made of lead contained in the insulating chamber, is then introduced into the cap and the external surface of the ceramic transducer is glued to the bottom of this cap with the epoxy resin. This configuration allows producing a satisfactory signal transmission into the liquid and can be used in many quite corrosive environments under high pressure. Projects are underway leading to development of ultrasonic probes which can be used in environments where the temperature goes up to 200°C.

VI. Results Obtained

VI.1. Calibration Curve of a 0-5 l/s Flowmeter

The assembly used is shown in Figure 8a. The flowmeter is installed at the outlet of a convergent connected to a large-capacity water tank (10 m^3). A valve installed in series with the sensor ensures the opening and closing of the circuit containing the flowmeter and whose output supplies a vessel made of a plastic substance and with a 130 liter capacity. Inside is located a stainless /69 steel cylinder whose lower part includes a series of holes avoiding the eddies occasioned by the liquid at flow rates greater than 0.5 l/s. On the wall of the tank there are two level detectors installed which trigger the start and stop of an electronic chronometer. A scale on which the tank is placed allows precise determination of the weight of the liquid which corresponds in this case to a mass of 60 kg of water, ensuring a satisfactory precision (on the order of 1%) for a maximum flow rate of 5 kg/s of water. It is enough, therefore, with this apparatus to read the time posted on the chronometer in order to determine the flow rate.

The curve obtained in this manner (Figure 8b) shows the linearity of the ultrasonic flowmeter being studied. It was thus able to ascertain that, under these experimental conditions wherein the flow is carefully adjusted, the perturbation contributed by the probes at the level of the flowmeter is only revealed by a very faint disturbance of the measurement performed.

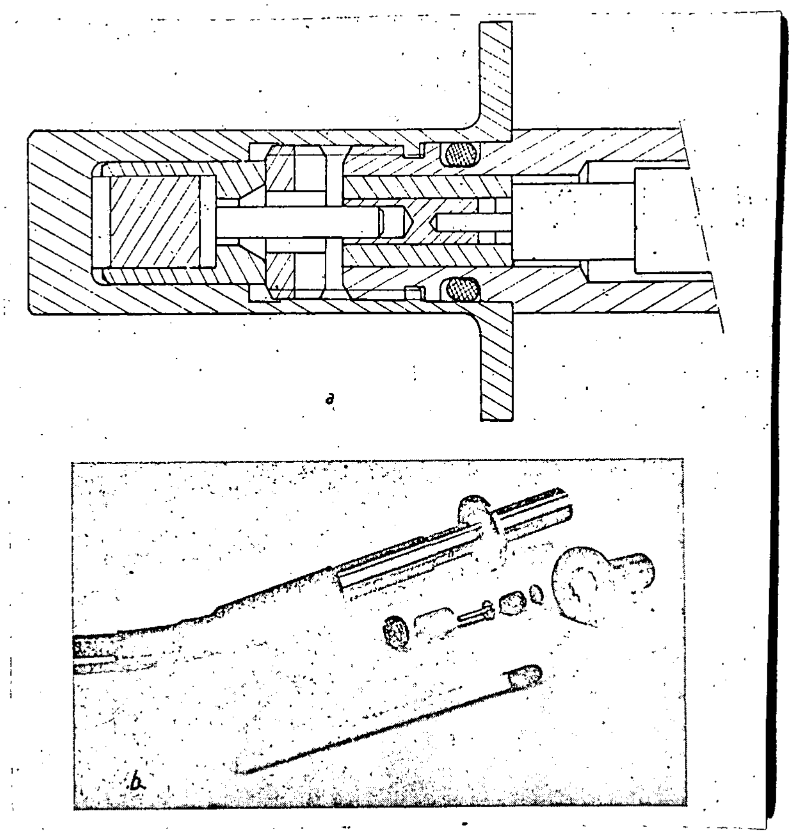

Figure 7. Ultrasonic probe.

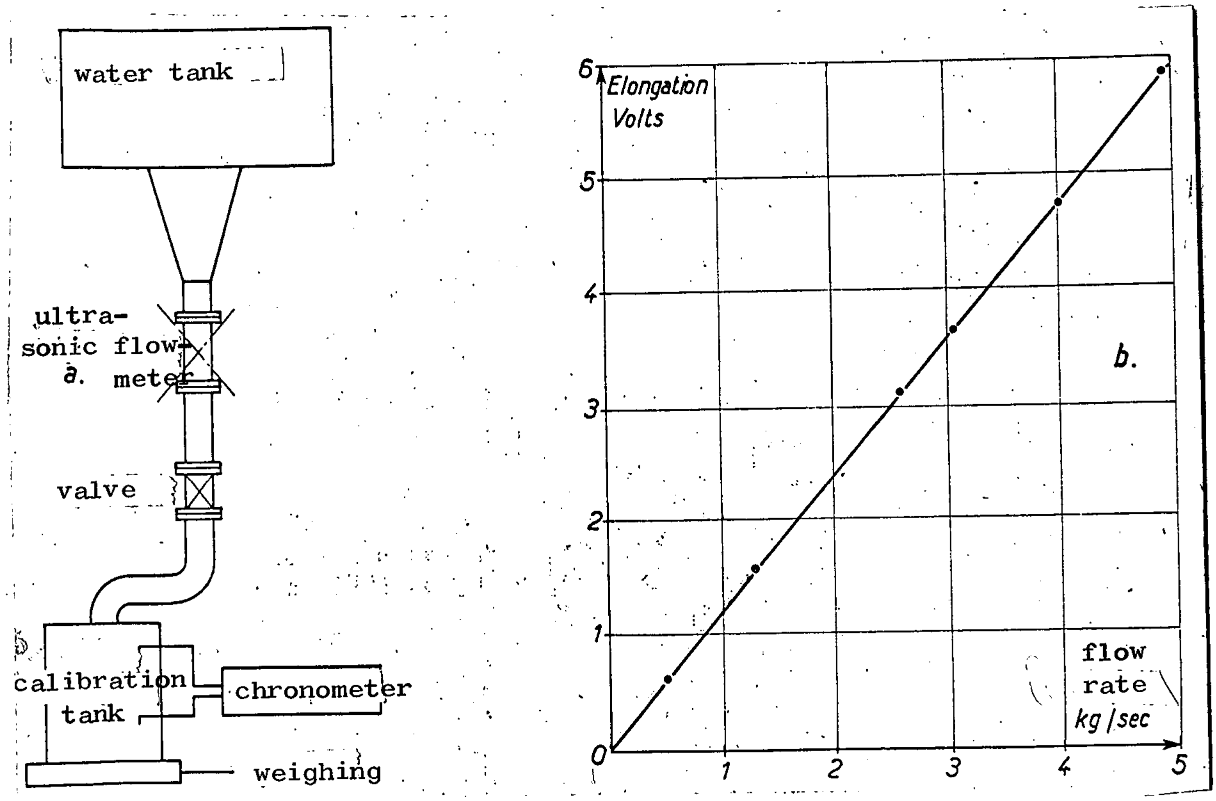

Figure 8. Calibration of the probe.

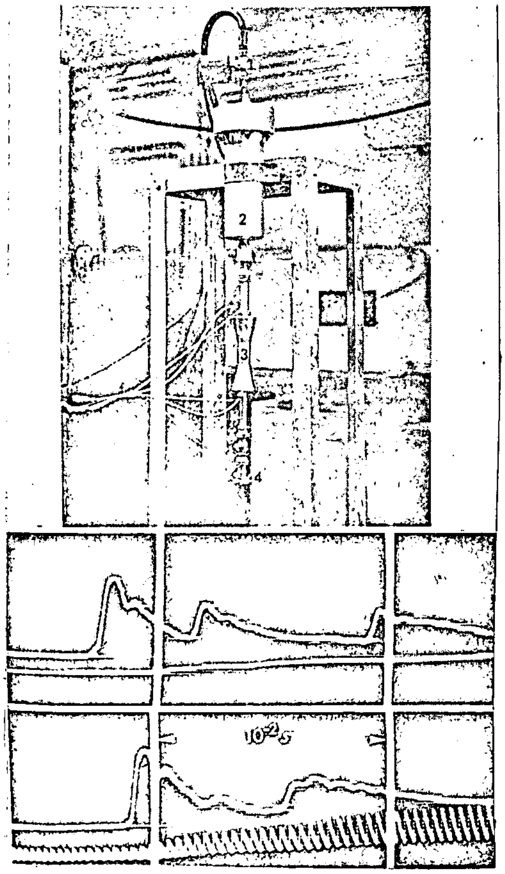

Figure 9. Response time measurement.

1 - solenoid valve
2 - tank
3 - ultrasonic flowmeter
4 - membrane

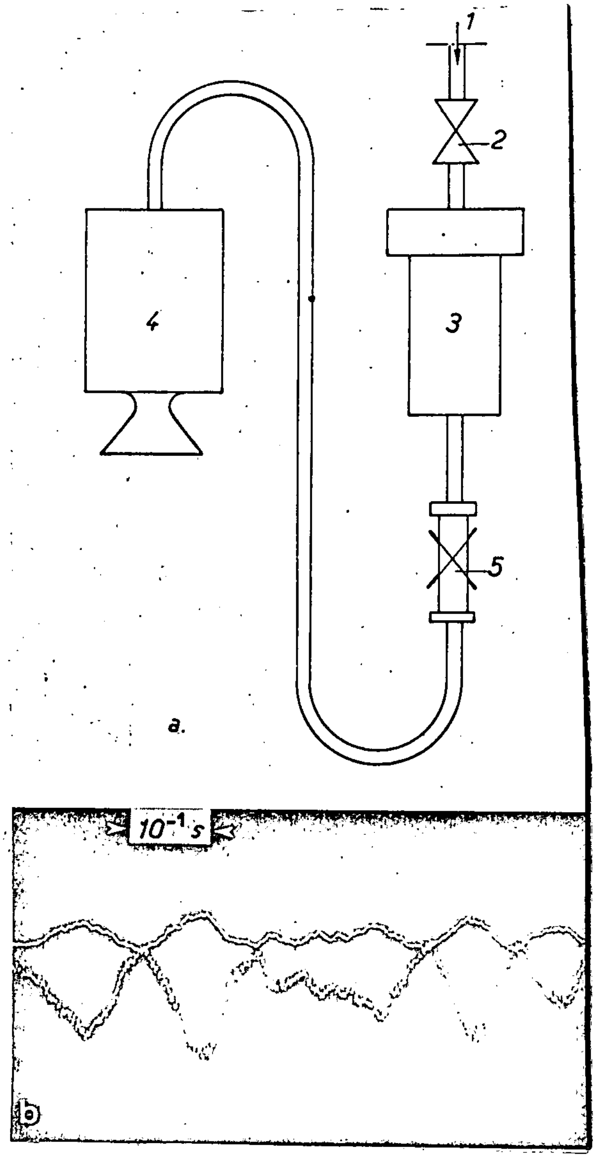

Figure 10. Flow rate to pressure correlation in a hybrid rocket engine.
1 - pressurizing the tank
2 - solenoid valve
3 - tank
4 - rocket engine
5 - ultrasonic flowmeter

VI.2. Response Time Measurement

The response of the flowmeter to a drop in flow rate has been studied experimentally. The apparatus is placed at the outlet of a tank of liquid on which it is possible to apply gas pressure with the help of a high-speed solenoid valve. A diaphragm, placed at the outlet of the flowmeter, limits the flow rate to a determined value which is a function of the range of the latter. The system is filled with water leaving, however, a small volume of air between the tank and the solenoid valve. The pressure is measured at the level of the diaphragm by a piezoelectric sensor with a very wide band pass (characteristic frequency of the membrane 40 Hz) made flush with the pipe wall.

When pressure is applied on the tank, the inside pressure increases and the membrane abruptly breaks at a specific value. There is then produced a rather well-defined step increase in flow rate. The pressure sensor indicates the instant of rupture of the membrane, defining in this way the origin of the phenomenon. The time of pressurizing the tank is a function of the air volume remaining between the tank and the solenoid valve. This time does not become a factor in the measurement since the origin is given by the instant of the pressure drop following the bursting of the membrane. Figure 9 shows a photo of the measuring device as well as two examples of recordings. The first one shows the general aspect of the voltage collected at the outlet of the analog chain; i.e. at the outlet of the low-pass filter. In the second one, there can be seen the sawtooth voltage picked off at the same instant at the outlet of the /70 differential amplifier processing the signals coming from both integrators. This is how the unfiltered calibrated measurement is obtained. The results from these tests show the high-speed response of this type of apparatus. In the first case, this time, as a consequence of the presence of the filter, is on the order of 2 ms. In the second case, this response time amounts to 1 ms. It should, nevertheless, be noted that these values can be lowered still more, as has been shown in the first part of this report, by reducing the time travel of the ultrasonic wave from one probe to another and, in this way, reducing the calibration time.

VI.3. Correlation Between The Flow Rate of Fuel and the Pressure Chamber in a Hybrid Rocket Engine

A flowmeter with a low 0-500 g/s flow rate is used for measuring a flow-rate of fuel (nitric acid) in a hybrid rocket engine. Figure 10 shows the correlation produced between the variations of flow rate as well as pressure. Indeed, in such a type of rocket engine, when the chamber pressure increases the difference in pressure between the chamber and the injection tank decreases causing a decrease in the fuel flow rate. This is the phenomenon seen with recording of pressure chamber and acid flow rate parameters during a rocket engine launch, voluntarily adjusted for a very unstable operation.

VI.4. Use of a 0.1 l/s Flowmeter For Measurement of the Flow Rate of Chlorine Trifluoride (ClF_3).

The high-speed response time measurements of the flow rate of Clf_3 in hybrid rocket engines, for example, are normally carried out at O.N.E.R.A. using paddle-type flowmeters. These apparatus operate reliably but, nevertheless, have the disadvantage of introducing a material obstacle into the flow and only having a relatively reduced dynamics (on the order of 10) which is low when compared with that of the ultrasonic flowmeter reaching 100. This last advantage is quite valuable for those applications where, owing to the special properties of ClF_3, the manipulations are difficult and the disassembling of a component on the bench is followed by a rather long delay before resuming operation (passivation of the pipes). Now, the flow rates can vary greatly from one launch to another leading, in the case of the paddle-type flowmeter, to a change of sensor. Figure 11 shows a photo of the rocket engine bench as well as the flow rate of the recording of a test made on a rocket engine fitted with a unit of solid fuel ignited by injection of ClF_3. In this special case, there may be ascertained a slight unstable coupling between flow rate and pressure. During this test, a paddle-wheel flowmeter designed at O.N.E.R.A. was installed in series in the pipe for injecting the ClF_3. The recording of the flow rate as a function of time shows the superiority of the ultrasonic flowmeter, reproducing much more faithfully the oscillations of the beginning of the test.

VI.5. Examples of Sensors in Production

Various apparatus have been built and are used for special applications:

(a) 0.5 l/s flowmeter, used for basic research in non-steady state hydraulics (Figure 12);

(b) 0-1 l/s flowmeter, used for measurement of flow rates of liquids investigated in rocket engine test beds;

(c) 0-5 l/s flowmeter, used for basic research on a two-liquid rocket engine. It allows study of a flow rate of extraction which can be modulated up to a frequency of a hundredth of a hertz (Figure 14).

D

(d) 0-25 l/s flowmeter, for measurement of the flow rate of fuel (UDMH) in a two-liquid rocket engine (Figure 15);

(e) 0-100 l/s flowmeter, for measurement of the flow rate of the oxidizer (nitrogen peroxide) in a two-liquid rocket engine (Figure 16).

The apparatus pointed out in c, d and e are especially designed for research on th POGO instabilities of Diamont launch vehicles.

VII. Conclusion

The results obtained during this study of development of ultrasonic flowmeters can be ordered into two distinct categories:

Since the measurement is made on the pipe itself, the minimum of modifications is applied to the circuit of the liquid.

The probes are attached to the wall of the tube since the angle formed by them with the chief flow axis is a function of the diameter and maximum velocity of the fluid. With these conditions satisfied, the tube component behaves like a flowmeter. However, as a consequence of the impossibility of acting on the upstream flow, the signal arising from the local turbulence and superimposed on the one from the mean fluid velocity is a function of the geometery of the upstream circuit. Since the probes are always attached on the wall of the tube, the incidence of the turbulence on the flow rate signed can be minimized when precautions are taken with the shape of this upstream circuit (grids, rectilines part before the probes...).

The measurement can be made by means of a component added to the installation. In this case, a "flowmeter body" is interposed on the circuit with all precautions taken to avoid turbulences (connection venturi, imposed lengths). In this case, the perturbation of flow is limited to the eddies owing to the presence of the probes and generally can be disregarded.

This second mode should be selected whenever possible. It frequently happens that the liquid flow-rate is the main parameter. The first case remains more especially reserved for experiments in which knowledge of the flow rate is only one of the aspects of the problem of investigating characteristic instabilities of the circuit.

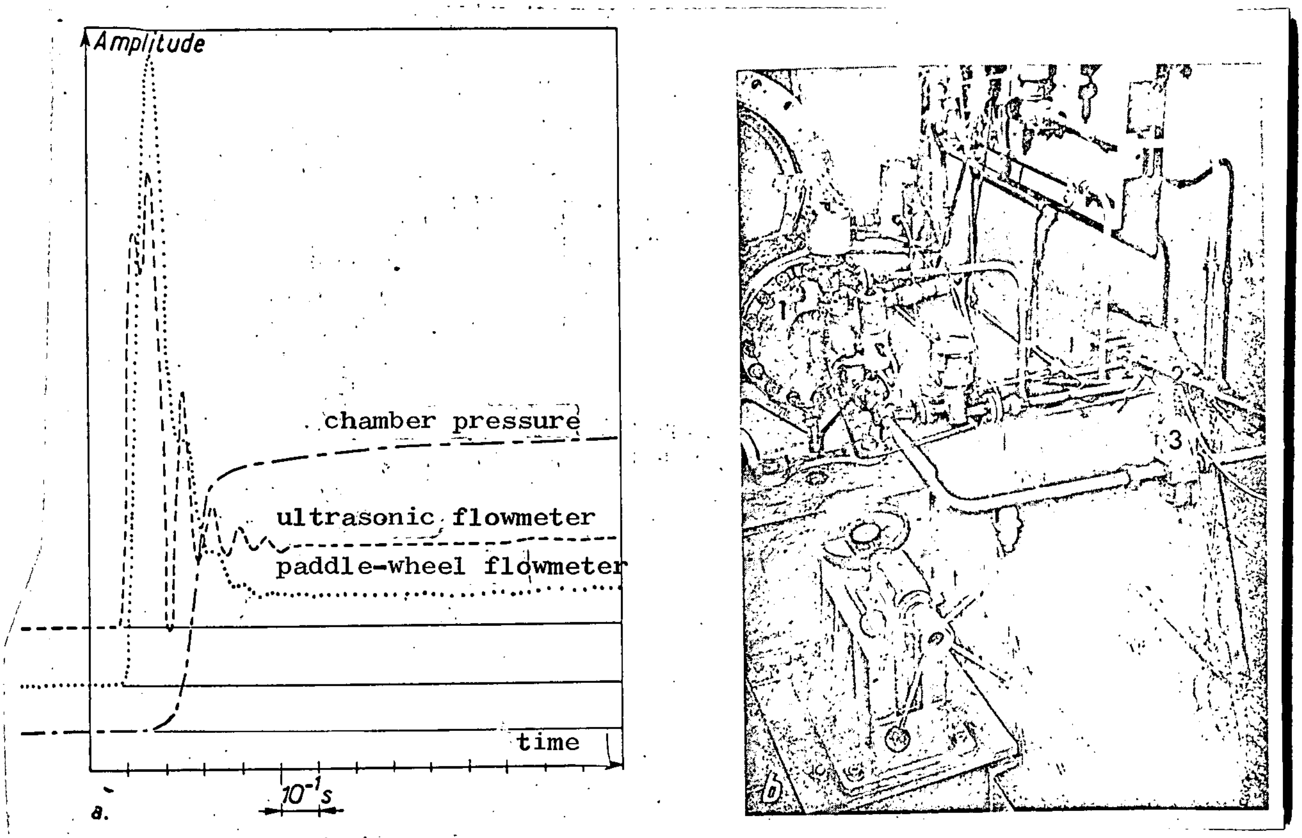

Figure 11. Flow rate measurement of ClF_3 in a hybrid rocket. Comparison of flow rates measured by various methods.

1 - rocket engine
2 - ultrasonic flowmeter
3 - paddle-wheel flowmeter.

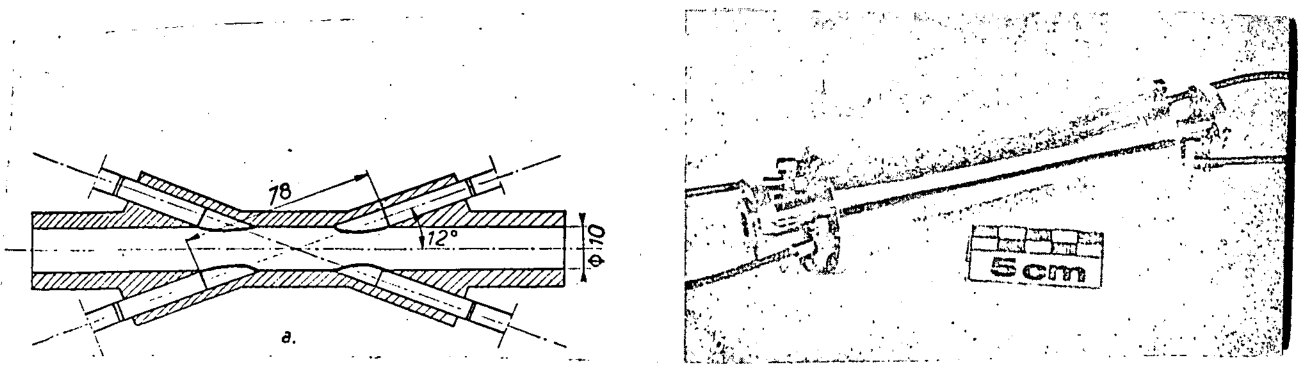

Figure 12. Ultrasonic flowmeter - 0-0.5 l/s.

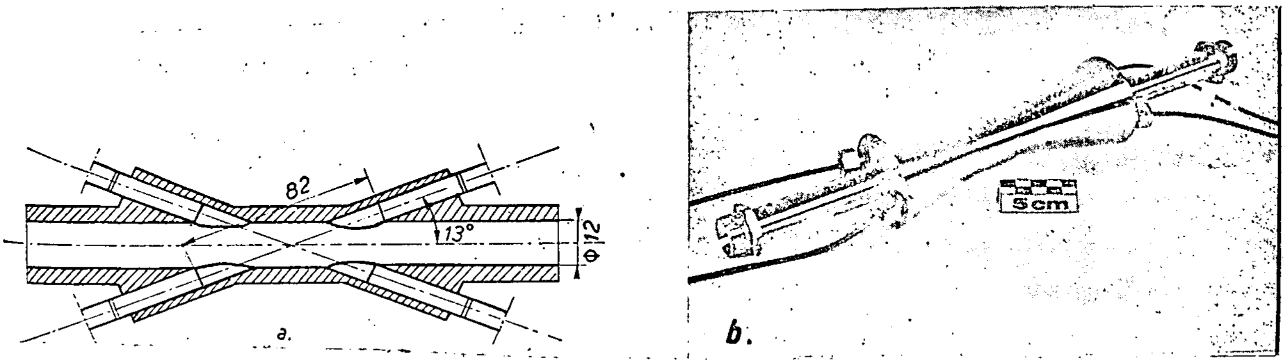

Figure 13. Ultrasonic flowmeter - 0-1 l/s.

The technique for measuring velocities of liquid fluid by ultrasonic means, therefore, allows handling specific research problems of a special configuration or taking action, in a more general way and using suitable sensors, in the measurement of the flow rate in its true sense. The examples provided in this article are related to both possibilities.

Experience shows that this method now has a high degree of reliability. The absence of mechanical systems, on one hand, and the development of a complex electronic system along the lines described but made technically quite reliable by the use of modern multifunctional components, have made it a select technique for research and industry. In the case where response time is secondary in importance, the electrical integration, by averaging the incidences of local turbulences, allows attainment of a high degree of precision. The nature of the fluid is less critical than with the systems with mechanical transducers. /73 In addition, to the absence of a mechanical threshold, these apparatus have a very extensive dynamics and provide excellent results with very viscous liquids and even with gels. On the other hand, the presence of suspensions of solids or gases should be avoided since they diffract the ultrasonic waves and prevent them from reaching the receiving probe.

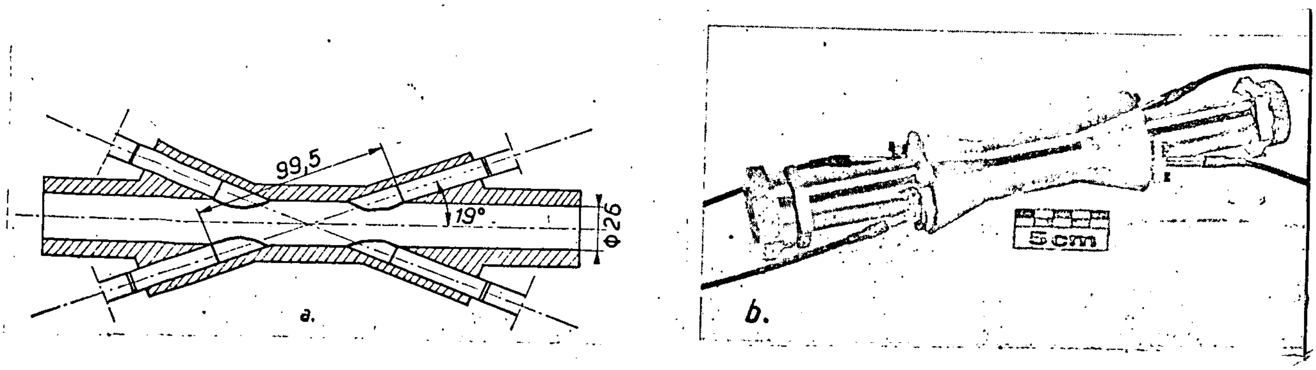

Figure 14. Ultrasonic flowmeter - 0-5 l/s.

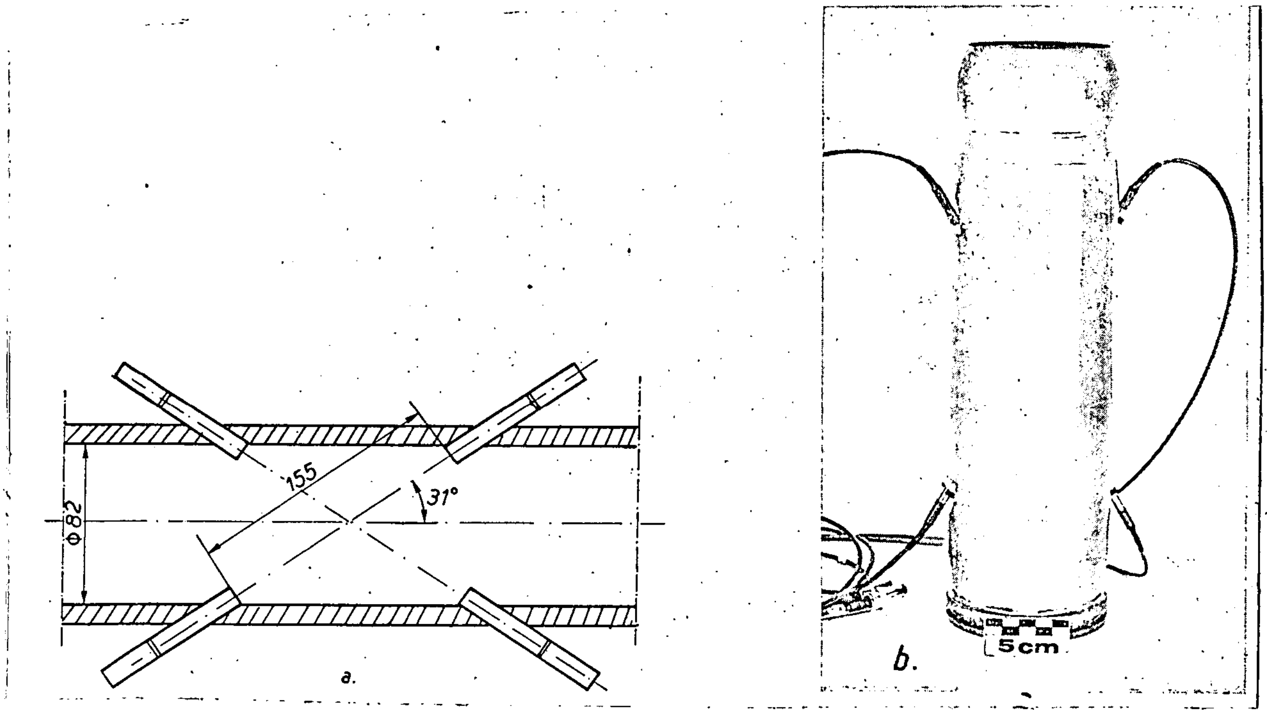

Figure 15. Ultrasonic flowmeter - 0-25 l/s.

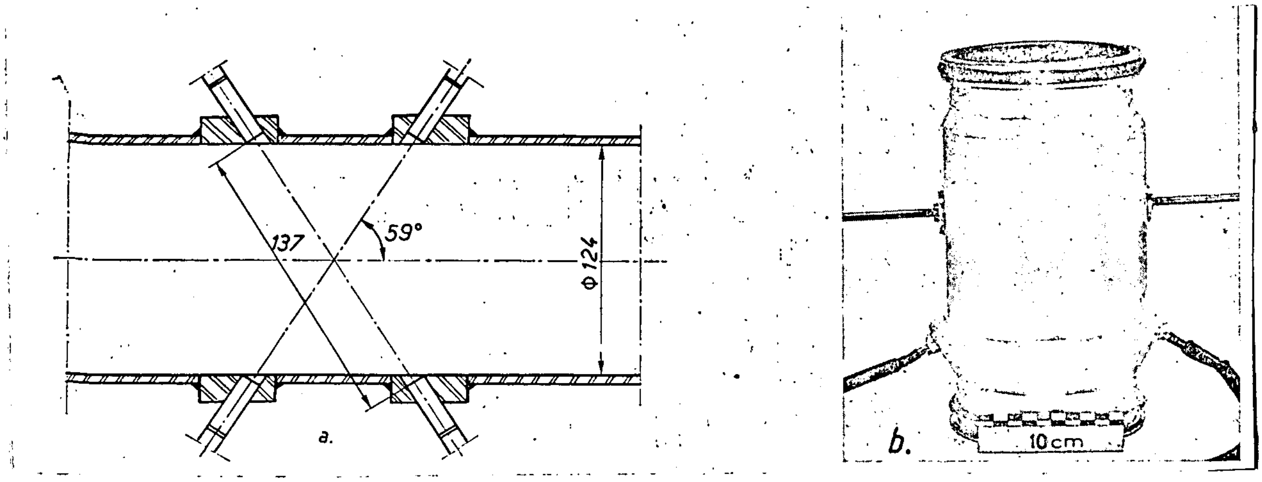

Figure 16. Ultrasonic flowmeter - 0-100 l/s.

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